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REVIEW

Development, Characterization, and Distribution of New, High-yielding, and Highly Palatable Japanese Rice Cultivars "Tsukiakari" and "Niji-no-kirameki"

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Abstract

As a consequence of extreme changes in climate, farming scale, and social structure, the requirements for rice yield potential and grain quality have been changing in Japan. To meet the demands of consumers, rice processing companies, and paddy farmers, "Tsukiakari" and "Niji-no-kirameki" were developed as high-yielding and highly palatable rice cultivars. The palatability of both cultivars is excellent and is as high as the leading Japanese cultivar, "Koshihikari." The yield potential of the new cultivars is over 700 g m^{-2} (brown rice, 15% moisture basis), and their shorter culm lengths provide greater lodging tolerance. "Tsukiakari" has been mainly distributed in the northern and central regions of Honshu, whereas "Niji-no-kirameki" has been distributed in the central and western regions. An early maturity cultivar, "Tsukiakari," is useful for separating harvest schedule from "Koshihikari." "Niji-no-kirameki" has been replacing "Koshihikari" in heat-vulnerable regions due to its superior heat resilience during the ripening period. Establishing proper cultivation methods for "Tsukiakari" and "Niji-no-kirameki" through multiple environmental tests helps local farmers efficiently manage their farms and produce high-yielding and highly palatable crops. Superior characteristics of "Tsukiakari" and "Niji-no-kirameki" will be useful to develop new rice genotypes that highly meet the needs of the times.

Discipline: Crop Science
Additional key words: climate change, cropping schedule, eating quality, large-scale farming, yield potential

Introduction

Rice consumption in Japan has changed significantly in recent decades due to several factors, including the decline in population and changes in lifestyle. Since peaking at 118.3 kg in 1962, annual rice consumption per capita has continued to decline and was estimated to be 50.7 kg in 2020 (Ministry of Agriculture, Forestry and Fisheries, Japan 2022a). Recently, total rice consumption has declined at a pace of about 100,000 tons per year (Ministry of Agriculture, Forestry and Fisheries, Japan 2021). The proportion of rice cooked in homemade meals has decreased, whereas rice cooked for commercial purposes and consumed as ready-to-eat meals (e.g., lunch boxes and rice balls sold in supermarkets and convenience stores) and dining out has increased. In change reflecting the tendency of Japan's population to prefer time-saving cooking styles due to changes in social structure, i.e., increases in single-person and double-income households, the proportion of rice used for commercial purposes was 15.2% in 1985, reached 30.8% in 2020, and is projected to exceed 40% in 2035 (Ministry of Agriculture, Forestry and Fisheries, Japan 2021; Rice Stable Supply Support Organization 2015).

There is a high demand for developing high-yielding varieties that are highly compatible with large-volume rice cooking. High yields are linked with cost-saving, and high compatibility will increase cooking efficiency. Rice

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used for ready-to-eat meals and dining out has different characteristics from rice cooked at home. Yanagihara & Fujii (2017) summarized the characteristics required for commercial rice cooked by a variety of processes based on interviews with rice processing companies. According to the report, essential parameters for cooking rice in large volumes include several characteristics: (i) high recovery during the milling process with a small amount of crushed rice, (ii) an increase in weight and volume due to rice steaming, (iii) an optimum level of stickiness after steaming for easy processing of the cooked rice, and (iv) the retention time needed for maintaining the best quality after cooking.

"Koshihikari" is a leading rice cultivar in Japan, and consumers like it because of its high quality, good taste, and sticky texture. However, for the requirement to process commercial rice in large volumes, "Koshihikari" is not the best rice grain. In addition, "Koshihikari" is very susceptible to lodging because of its slender plant phenotype (Kobayashi et al. 2018). Thus, farmers need to grow "Koshihikari" with particular care in fertilizer management. Recently, the scale of paddy farming in the Hokuriku region has increased against the background that aging farmers running small-scale farms have handed off their paddy fields to younger farmers who prefer large-scale farming (Hosoyama 2016). In a large-scale farm, cultivars with different maturities and high tolerance to lodging must be grown to maximize work efficiency at harvest. Growing "Koshihikari" with large scale is not the proper style for large-scale field management. Another challenge in producing high-quality rice is global warming. Rising temperatures during the ripening period deteriorate rice grain quality in Japan (Morita et al. 2016). Chalky grains caused by high temperature stress decrease commercial value of rice, resulting in an economic loss of rice producers (Morita et al. 2016). There is a wide variation in occurrence of chalky grains under high temperature stress during the ripening period among cultivars (Kaji et al. 2016, Kobayashi 2012, Tamura et al. 2018). Highly palatable cultivars that are resilient to high-temperature stress are needed because the heat resilience of "Koshihikari" is not sufficient (Kaji et al. 2016, Kobayashi 2012).

To meet the demands of rice consumers, rice processing companies, and paddy farmers, the National Agriculture and Food Research Organization (NARO) has been intensively working in recent years to develop promising cultivars with high yields, high palatability, high resistance to lodging, high heat resilience and also high compatibility for rice cooking (The Institute of Crop Science, NARO 2020). Two promising cultivars, "Tsukiakari" and "Niji-no-kirameki," were developed recently at the Joetsu Research Station, Central Agricultural Research Center, NARO and they have both been distributed throughout Japan. In this review paper, we report on the breeding process, characteristics, and distribution of both cultivars.

Development and characterization of "Tsukiakari"

"Tsukiakari" was bred from the progeny of a three-way cross of "Kabashiko" (JP10698) / "Hokuriku 200" (later it was released as "Mizuho-no-kagayaki" (Shigemune et al. 2015)) // "Hokuriku 208." Grain yield, yield components, other key traits related to plant phenotype, grain appearance, and disease resistance of "Tsukiakari" are shown in comparison with the Japanese high quality cultivar, "Akitakomachi" (Table 1). The heading and maturing dates of "Tsukiakari" are almost the same as those of "Akitakomachi," respectively, which is approximately one to two weeks earlier than those of "Koshihikari" (Sasahara et al. 2018). Compared with "Akitakomachi," the culm length is shorter by 10 cm in "Tsukiakari," supporting the superior lodging tolerance of "Tsukiakari" compared to "Akitakomachi" (Fig. 1; Ishimaru et al. 2022a). The panicle length of "Tsukiakari" is slightly longer, and there are fewer panicles compared with "Akitakomachi," respectively. Grain yield is higher in "Tsukiakari" by approximately 10% than that of "Akitakomachi." Ishimaru et al. (2022a) demonstrated that the yield potential of "Tsukiakari" is as much as 750 g m^{-2}. The 1,000-grain weight is higher in "Tsukiakari" by approximately 10% compared to "Akitakomachi." The grain appearance of "Tsukiakari" is occasionally inferior to that of "Akitakomachi," mainly due to the white belly type of grain chalkiness (Table 1). The genetic factors for the increased number of white belly grains in the "Tsukiakari" need to be investigated further.

The eating quality of cooked "Tsukiakari" rice is equal to or superior to that of "Koshihikari," which is regarded as having high eating quality (Table 2; Sasahara et al. 2018). "Kabashiko" was chosen as a parent in the breeding of "Tsukiakari" because the eating quality of "Kabashiko" was relatively superior among native Japanese rice varieties (Sasahara et al. 2017). The superior eating quality of cooked "Tsukiakari" rice might be derived from "Kabashiko." Further studies are required to understand the genetic factors and physicochemical properties that contribute to the high eating quality of "Tsukiakari."

Development and characterization of "Niji-no-kirameki"

"Niji-no-kirameki" was bred from the progeny of a cross of "Seinan 136" (later it was released as "Natsuhonoka" (Wakamatsu et al. 2016)) / "Hokuriku 223." Grain yield, yield components, other key traits related to plant phenotype, grain appearance, and the disease resistance of "Niji-no-kirameki" are shown in comparison with the Japanese high quality cultivar, "Koshihikari" (Table 3). The heading date and maturing date of "Niji-no-kirameki" are almost the same and four days later than those of "Koshihikari," respectively. Compared with "Koshihikari," the culm length is shorter

Table 1. Characteristics of "Tsukiakari"

	Heading date (m.dd)	Maturing date (m.dd)	Culm length (cm)	Panicle length (cm)	Panicle number (m^{-2})	Yield ($g\ m^{-2}$)	1,000-grain weight (g)
"Tsukiakari"	7.27	9.01	77***	20.0**	310*	646†	23.9**
"Akitakomachi"	7.26	8.31	87	18.5	399	591	21.5

	Degree of lodging[a] (0~5)	Resistance: Blast – Leaf	Resistance: Blast – Panicle	Resistance: Rice stripe virus	Resistance: Cold at the booting stage	Resistance: Pre-harvest sprouting
"Tsukiakari"	0.8	medium	medium	sensitive	slightly strong	strong
"Akitakomachi"	1.0	medium	slightly weak	sensitive	medium	slightly strong

	Grain appearance[b]: Overall (0~9)	White belly (0~9)	White Core (0~9)	Milky White (0~9)	Basal white & white back (0~9)
"Tsukiakari"	5.0	2.0*	1.2	1.1	2.1†
"Akitakomachi"	4.9	0.2	1.0	1.1	3.4

This table was made in part, with data presented in Sasahara et al. (2018).
The scores are the average of five years.
The basal fertilizer consisted of 4 g m^{-2} each of N, P_2O_5, and K_2O, and as the additional fertilizer, 2 g m^{-2} of N, 0.8 g m^{-2} of P_2O_5, and 3 g m^{-2} of K_2O were applied at approximately 25 days before heading.
The compost was applied approximately 1,000 g m^{-2} every year.
[a] Degree of lodging was evaluated by visual inspection as 0 (no lodging) to 5 (extensive lodging).
[b] Overall grain appearance was evaluated by visual inspection as 1 (very superior) to 9 (very inferior) and other grain appearance parameters were evaluated as 0 (no chalk) to 9 (terribly chalked), respectively.
***, **, * and † indicate significance at 0.1%, 1%, 5%, and 10% level between genotypes by *t*-test.

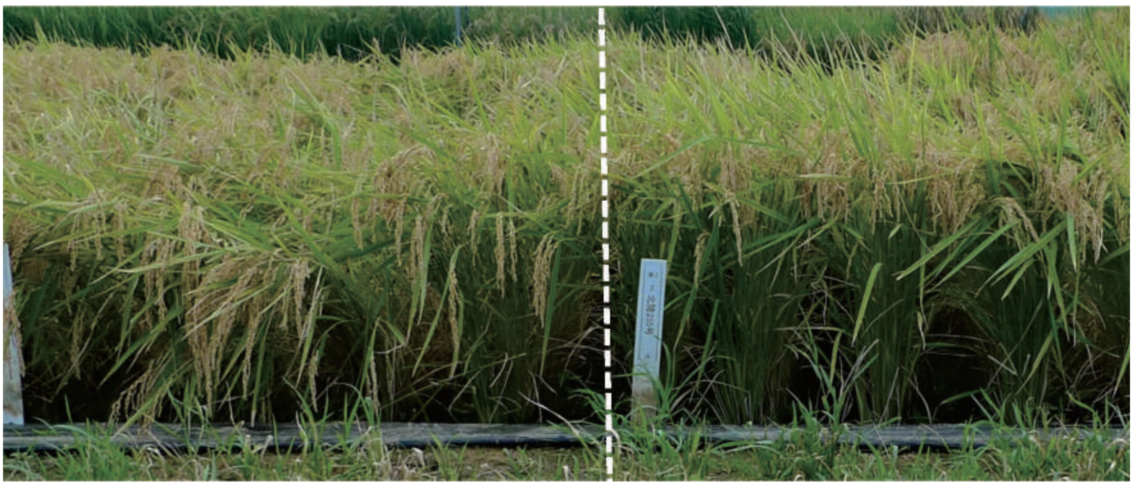

Fig. 1. Field appearance of "Akitakomachi" (left) and "Tsukiakari" (right)

by 25 cm, the panicle length is slightly longer, and the panicle number is slightly larger. The lodging tolerance of “Niji-no-kirameki” is much higher than that of “Koshihikari” because of the short culm length (Table 3; Fig. 2). In 2020, the lodging tolerance of “Niji-no-kirameki” helped farmers increase their harvesting time efficiency in a paddy field in Niigata Prefecture, where lodging of “Koshihikari” was too severe to efficiently and smoothly harvest the crop. Grain yield is higher in “Niji-no-kirameki” by 10% compared to “Koshihikari.” The 1,000-grain weight of “Niji-no-kirameki” is greater than that of “Koshihikari” (Table 3). Up to date, yield trial showed that grain yield of “Niji-no-kirameki” is as high as 758 g m^{-2} (Nagaoka et al. 2020).

The overall grain appearance of “Niji-no-kirameki” is superior to that of “Koshihikari.” The difference is due to the presence of basal-white and white-back grains (Table 3), which are known to be formed due to high temperature stress during the ripening period (Wakamatsu et al. 2007). The superior performance of “Niji-no-kirameki” during high temperature stress might be inherited from “Natsuhonoka” (Wakamatsu et al. 2016), which was the parent of “Niji-no-kirameki” (Nagaoka et al. 2020). The frequency of chalky grains increases in “Koshihikari” when the average daily mean temperature during the first 20 days after heading is over

Table 2. Eating quality of “Tsukiakari”

	Overall (–5~+5)	Appearance (–5~+5)	Aroma (–5~+5)	Umami (–5~+5)	Smoothness (–5~+5)	Stickiness (–5~+5)	Hardness (–5~+5)
“Tsukiakari”	1.12**	1.12***	0.46	0.82**	0.83	1.06	–0.28*
“Akitakomachi”	0.55**	0.50*	0.36	0.55	0.44***	0.51***	–0.14***
“Koshihikari”	0.84	0.68	0.34	0.56	0.74	0.97	–0.48

Each score was rated in comparison with “Nipponbare” representing a cultivar of average palatability (= 0).
The scores are the average of five examinations. The number of evaluators ranged from 22 to 31.
The higher the scores, the better the performance in appearance, aroma, and umami; the more smooth, sticky, and hard; and the better overall.
***, **, and *: Significant at levels of 0.1%, 1% and 5% between “Koshihikari,” respectively, according to a *t*-test.

Table 3. Characteristics of “Niji-no-kirameki”

	Heading date (m.dd)	Maturing date (m.dd)	Culm length (cm)	Panicle length (cm)	Panicle number (m^{-2})	Yield (g m^{-2})	1,000-grain weight (g)
“Niji-no-kirameki”	8.05	9.18	71***	19.6	416	719*	24.6***
“Koshihikari”	8.05	9.14	96	19.0	399	627	22.4

	Degree of lodging[a] (0~5)	Resistance				
		Blast		Rice stripe virus	Cold tolerance at the booting stage	Pre-harvest sprouting
		Leaf	Panicle			
“Niji-no-kirameki”	0.0***	medium	slightly strong	resistant	weak	strong
“Koshihikari”	4.2	weak	weak	sensitive	medium	strong

	Grain appearance[b]				
	Overall (0~9)	White belly (0~9)	White Core (0~9)	Milky White (0~9)	Basal white & white back (0~9)
“Niji-no-kirameki”	4.0***	0.5	1.0*	0.6**	1.1*
“Koshihikari”	5.8	0.8	1.9	1.9	3.2

This table was made in part, with data presented in Nagaoka et al. (2020).
The scores are the average of five years.
The basal fertilizer consisted of 4 g m^{-2} each of N, P_2O_5, and K_2O, and as the additional fertilizer, 2 g m^{-2} of N, 0.8 g m^{-2} of P_2O_5, and 3 g m^{-2} of K_2O were applied at approximately 25 days before heading.
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***, **, * and † indicate significance at 0.1%, 1%, 5%, and 10% level between genotypes by *t*-test.

27°C (Ishimaru et al. 2018, Sugiura et al. 2013, Terashima et al. 2001, Wakamatsu et al. 2007). Loosely-packed amyloplasts cause the chalky phenotype (Tashiro & Wardlaw 1991). Detailed quantification and the possible reason for the superior grain appearance of "Niji-no-kirameki" under high-temperature stress during the ripening period will be described in the following section. The eating quality of cooked "Niji-no-kirameki" rice is equal to that of "Koshihikari" (Table 4). Moreover, "Niji-no-kirameki" is resistant to the rice stripe virus, attributed to the *Stvb-i* gene derived from "Satojiman" (Sato et al. 2013) through "Hokuriku 223." We expect that "Niji-no-kirameki" will be distributed rapidly because it has several characteristics that are superior to those of "Koshihikari."

Distribution of "Tsukiakari" and "Niji-no-kirameki" to farmers' fields

"Tsukiakari" and "Niji-no-kirameki" have been distributed throughout Japan. In 2022, "Tsukiakari" and "Niji-no-kirameki" were designated as brand varieties of the growing districts in 16 and 13 prefectures, respectively (Fig. 3). "Tsukiakari" has been grown mainly in the Tohoku region and in the hilly-mountainous warm region in the western part of Japan, replacing "Akitakomachi" and other cultivars. In contrast, "Niji-no-kirameki" has been grown mainly in the Kanto and the western regions, where grain chalkiness caused by high temperatures and rice stripe disease emerge frequently. "Niji-no-kirameki" may not be adaptable in the Tohoku region because of its weakness of cold tolerance at the booting stage (Nagaoka et al. 2020).

Optimization of grain yield, grain quality, and the cropping schedule for "Tsukiakari" and "Niji-no-kirameki"

1. General cultivation method

Prior to variety release, multi-environmental testing of cultivars "Tsukiakari" and "Niji-no-kirameki" was conducted in a wide range of regions in Japan. The maturity of "Tsukiakari" and "Niji-no-kirameki" was similar to that of "Akitakomachi" and "Koshihikari,"

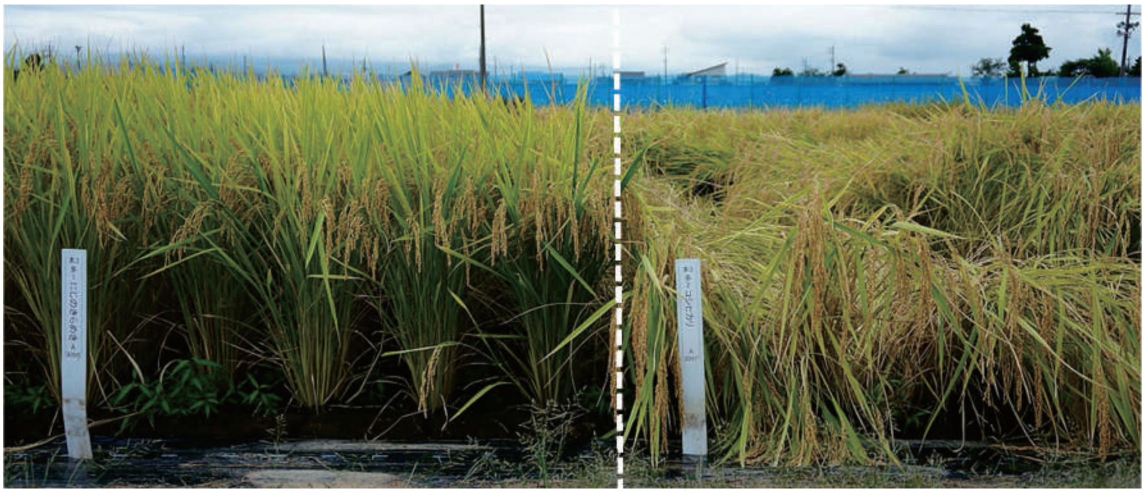

Fig. 2. Field appearance of "Niji-no-kirameki" (left) and "Koshihikari" (right)

Table 4. Eating quality of "Niji-no-kirameki"

	Overall (–5~+5)	Appearance (–5~+5)	Aroma (–5~+5)	Umami (–5~+5)	Smoothness (–5~+5)	Stickiness (–5~+5)	Hardness (–5~+5)
"Niji-no-kirameki"	1.12	1.09	0.61	0.95	1.04	1.23	–0.90*
"Koshihikari"	0.97	1.02	0.45	0.86	0.82	1.06	–0.57

Each score was rated with "Nipponbare" representing average palatability (= 0).
The scores are the average of five examinations. The number of evaluators ranged from 22 to 24.
The higher the scores, the better the performance in appearance, aroma and umami; the more smooth, sticky and hard; and the better overall.
*: Significant at a level of 5% between "Koshihikari," according to a *t*-test.

respectively, in all regions of Japan (Nagaoka et al. 2020, Sasahara et al. 2018), indicating that farmers can consider the basic cropping schedule for these cultivars to be identical to those of "Akitakomachi" and "Koshihikari." There are, however, some major differences in the amount and timing of fertilizer application and the optimum stage for harvesting "Tsukiakari" and "Niji-no-kirameki" compared with "Akitakomachi" and "Koshihikari." The lodging tolerance of "Tsukiakari" and "Niji-no-kirameki," owing to their short culms, allows farmers to grow these cultivars in heavy fertilizer conditions to achieve high yields. For example, a 9.0-12.0 g m^{-2} nitrogen basis fertilizer is recommended for "Tsukiakari" and "Niji-no-kirameki" to achieve high yields (Central Agricultural Research Center 2019,2020). A 4.0-6.0 gm^{-2} nitrogen basis fertilizer is recommended for "Koshihikari" (Niigata Prefecture 2011); therefore, farmers can apply 1.5-2.0 times more nitrogen fertilizer to "Tsukiakari" and "Niji-no-kirameki" compared to "Koshihikari." Another critical difference is the timing of nitrogen fertilizer application as a topdressing. Nitrogen fertilizer can be applied as a topdressing around 25-30 days and 15 days before heading in "Tsukiakari" and "Niji-no-kirameki" (Central Agricultural Research Center 2019, 2020). Topdressing around 30 days before heading has a positive effect on increasing the grain yield by increasing the spikelet number per square meter in Japonica Group cultivars (Fukushima 2007, Wang et al. 1997), whereas topdressing increases the lodging risk through elongation of internode sections. The short culms of "Tsukiakari" and "Niji-no-kirameki" are compatible with high yields under heavy fertilizer conditions. The cumulative daily mean temperature during ripening determines the optimum harvesting stage at 1,100°C and 1,200°C for "Tsukiakari" and "Niji-no-kirameki," respectively (Central Agricultural Research Center 2019, 2020), whereas it is at 950°C-1,000°C for "Koshihikari" (i.e., Niigata Prefecture 2011). "Tsukiakari" and "Niji-no-kirameki" require longer days from heading to harvesting because of their high-yielding characteristics.

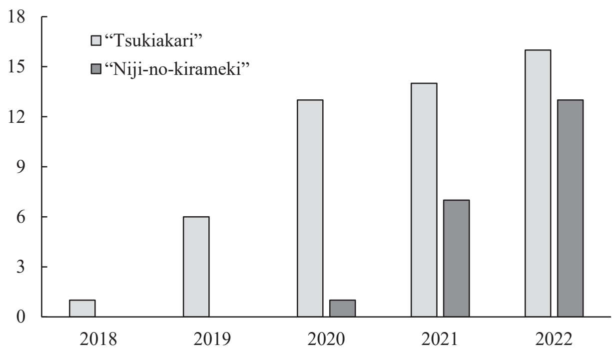

Fig. 3. Change of numbers of prefectures that designate "Tsukiakari" and / or "Niji-no-kirameki" as brand varieties of the growing district
This figure was made with reference to the Ministry of Agriculture, Forestry and Fisheries, Japan (2022b).

2. Key characteristics of "Tsukiakari" to achieve high yields and high palatability

Forty-seven yield trials in the Hokuriku region revealed that the spikelet number per square meter is positively correlated with grain yield in "Tsukiakari," but grain yield reached a plateau around 750 g m^{-2} (brown rice, 15% moisture basis) (Ishimaru et al. 2022a). The spikelet number per square meter must be over 35,700 when a maximum grain yield of 750 g m^{-2} is targeted (Table 5). Panicle number per square meter is the most critical key yield component for achieving high yields, suggesting that the promotion of tillering until the beginning of the reproductive stage is critical for ensuring a sufficient number of panicles (Ishimaru et al. 2022a). Based on an analysis at the harvesting stage, the relationship between yield attributes and grain quality can be represented as a significant linear regression model, as indicated in Table 5. The theoretical values for each trait at the maximum grain yield of 750 g m^{-2} are also shown in Table 5. The average grain yield of "Koshihikari" in Niigata Prefecture was 540 g m^{-2}; the yield advantage in "Tsukiakari" is expected to give an incentive to farmers to grow this cultivar to increase their income and farm management efficiency. Notably, attention must be paid to culm length to achieve the maximum yield of "Tsukiakari," where "Tsukiakari" has lodging tolerance, but the risk of lodging significantly increases when the culm length is over 83 cm (Ishimaru et al. 2022a). To avoid the risk of reducing harvesting efficiency, the culm length for "Tsukiakari" should be approximately 80 cm. Overall, our results showed that "Tsukiakari" is a high-yielding elite cultivar with high palatability and a low probability of lodging.

3. Quantification of heat-resilience in "Niji-no-kirameki" during the ripening period

Recent trends in elevated temperatures during the ripening period deteriorate the grain appearance of "Koshihikari." Niigata is the largest "Koshihikari"-producing prefecture with premium quality in Japan. Niigata Prefecture experienced a historically hot summer during the first 20 days after heading in August 2019, resulting in an extreme increase in chalky grains in "Koshihikari" (Ishimaru et al. 2020). The first grade of "Koshihikari" must contain over 70% of perfect grains (Ministry of Agriculture, Forestry, and Fisheries, Japan 2022c). "Koshihikari" is widely grown in the middle and western regions of Japan, but the heat resilience of "Koshihikari" is only moderate (Kaji et al. 2016, Kobayashi et al. 2012). With farmers currently demanding that rice genotypes with high palatability, high heat resilience and maturity properties similar to those of "Koshihikari" be developed, it is already challenging for farmers in the heat-vulnerable regions of Japan to obtain the top grade of "Koshihikari" (Morita et al. 2016). With "Niji-no-kirameki" being an excellent research material for determining how to achieve high heat resilience and palatability levels, elucidating the physiological mechanism(s) of heat-resilient genotypes is a critical target for Japanese rice scientists who must cope with the progressive warming climate (Ishimaru et al. 2016, Mitsui et al. 2016, Morita et al. 2016).

Because of the extreme high-temperature summer in 2019, grain samples of "Niji-no-kirameki" and "Koshihikari" were collected from experimental stations and farmers' fields in Niigata, Gunma, and Gifu Prefectures to conduct a multi-environmental comparative analysis of grain appearance between "Koshihikari" and "Niji-no-kirameki." The percentage of perfect "Koshihikari" grains tended to decrease when the average daily mean temperature during the first 20 days after heading was over 27°C, as reported previously (Ishimaru et al. 2018, Sugiura et al. 2013, Terashima et al. 2001, Wakamatsu et al. 2007), whereas that was not the case for "Niji-no-kirameki" (Fig. 4). Although evidence from a heat-vulnerable region in Japan, the Oura-Tatebayashi region of Gunma Prefecture, indicates only 18.5% of first grade of "Koshihikari" for the latest three years (2019-2021), 87.9% of first grade of "Niji-no-kirameki" (Table 6) was recorded for the first three years. "Niji-no-kirameki" is expected to boost the grain appearance in other heat-vulnerable regions in Japan, where an analysis of covariance revealed that the interaction of cultivars and daily mean temperature during the first 20 days after heading for the percentage of perfect grains was significant between the cultivars, while, based on the regression model for daily mean temperature during the first 20 days after heading and the percentage of perfect grains, "Niji-no-kirameki" was estimated to retain more than 70% perfect grains even when the daily mean temperature during the first 20 days after heading was 27.9°C (Fig. 4).

Where panicle temperature estimated by IM^{2}PACT (Yoshimoto et al. 2011) revealed that the difference

Table 5. Theoretical values calculated by a linear regression model developed by multi-environmental testing of "Tsukiakari" grown in the Hokuriku regions

Trait	Theoretical value	Remarks
Grain yield (g m^{-2})	750	Yield advantage over approximately 40% compared to 'Koshihikari.'
Spikelet number (m^{-2})	35.7	Calculated by a regression model; y = 17.8x+115.4 (r = 0.94***), wherein x represents spikelet number (m^{-2}), and y represents grain yield.
Panicle number (m^{-2})	423	Calculated by a regression model; y = 1.11x+280.2 (r = 0.83***), wherein x represents panicle number (m^{-2}), and y represents grain yield.
Spikelet number (panicle^{-1})	84.4	Calculated by theoretical values of spikelet number (m^{-2}) and panicle number (m^{-2}).
Filled grains (%)	83.8	Calculated by a regression model; y = −0.78x+111.6 (r = −0.83***), wherein x represents spikelet number (m^{-2}), and y represents filled grains (%).
1,000-Grain weight (g)	25.1	Calculated by theoretical values of grain yield and other three yield components
Shoot nitrogen content (g m^{-2})	14.0	Calculated by a regression model; y = 44.8x+120.8 (r = 0.90***), wherein x represents shoot nitrogen content, and y represents grain yield.
Perfect grains (%)	72.5	Calculated by a regression model; y = −1.20x+115.3 (r = −0.91***), wherein x represents spikelet number (m^{-2}), and y represents perfect grains (%).
Grain protein content (%)	7.1	Calculated by a regression model; y = 0.067x+4.67 (r = 0.78***), wherein x represents spikelet number (m^{-2}), and y represents grain protein content (%).

A regression model between traits and theoretical values at a grain yield of 750 g m^{-2} is presented in Ishimaru et al. (2022a).
*** indicates significance at 0.1% level.

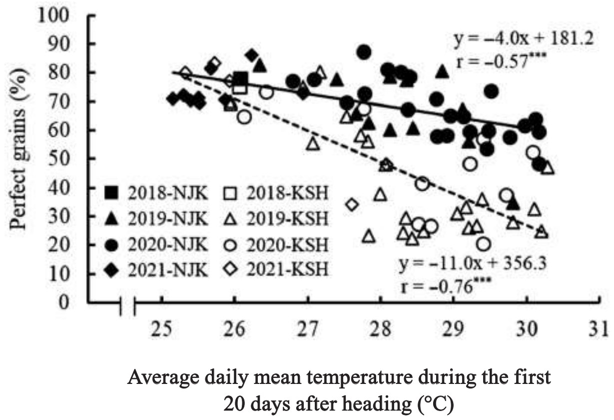

Fig. 4. Relationship between the average daily mean temperature during the first 20 days after heading and the percentage of perfect grains from multi-environmental testing in 2018-2021
NJK: "Niji-no-kirameki." KSH: "Koshihikari."
Data is adopted from Ishimaru et al. (2022b).

Table 6. Percentage of the first grade (%) of "Niji-no-kirameki" and "Koshihikari" grain produced in the Oura-Tatebayashi area of Gunma Prefecture

Year	First grade (%)	
	"Niji-no-kirameki"	"Koshihikari"
2019	80.0	5.6
2020	92.7	19.3
2021	90.9	30.5
Average	87.9	18.5

Data were provided by the Japan Agricultural Co-operatives of Oura-Tatebayashi.

in panicle temperature between "Niji-no-kirameki" and "Koshihikari" (subtraction of "Niji-no-kiraeki"–"Koshihikari") was not observed when the air temperature at 11:00-12:00 was up to 27°C, whereas it became negative when the air temperature was higher than 27°C (Ishimaru et al. 2022b), a study by Ishimaru et al. (2022b) found a novel biological response of "Niji-no-kirameki" that prevents an increase in panicle temperature when rising temperatures occur during the ripening period. The difference in panicle temperature between "Niji-no-kirameki" and "Koshihikari" was estimated to reach up to 1.6°C on the day of extremely high temperatures due to a foehn wind on 15 August 2019. This result suggests that "Niji-no-kirameki" adopts a "heat-avoidance" mechanism to retain a high level of grain appearance under high temperature stress. The unique plant architecture of "Niji-no-kirameki" was hypothesized to prevent direct solar radiation on the panicles, and the panicles' position in the canopy contributed to the "heat-avoidance" mechanism of this cultivar (Yoshimoto et al. 2011). The existence of a proposed "heat-avoidance" mechanism in "Niji-no-kirameki" provides a new concept for rice breeders to consider as they strive to develop heat-resilient rice genotype during the ripening period, where we see that modification of plant architecture may be a worthy challenge for upgrading heat resilience during the ripening period; differences in grain appearance between genotypes experiencing high temperature stress have been proposed to indicate heat "tolerance" during the ripening period.

Future prospects

In terms of crop acreage, "Koshihikari" is still the best rice cultivar in Japan, but the trend in rising temperatures during the ripening period and increases in farming scale have made it difficult for farmers to grow high quality "Koshihikari" with intensive management in some regions of Japan. Consumer preference for the sticky texture of "Koshihikari" has also been changing. It has been only seven and five years since "Tsukiakari" and "Niji-no-kirameki," respectively, were developed, but local farmers highly favor both cultivars because of their high yields, high palatability and other superior characteristics. Cultivation methods for "Tsukiakari" and "Niji-no-kirameki" should be optimized by extensive efforts of local agronomists and farmers in each prefecture to adjust to local climatic conditions. Superior eating quality of "Tsukiakari" and heat-avoidance mechanism in "Niji-no-kirameki" will give impacts on further development of new rice genotypes that highly meet the future demands of rice consumers, rice processing companies, and paddy farmers.

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